STOCHASTIC EVALUATION OF THE IMPACT OF DISTRIBUTED SYNCHRONOUS GENERATION ON VOLTAGE SAG PERFORMANCE

Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science Electrical Engineering in Power and Energy Systems

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Abstract

Voltage sags are caused by faults which cause equipment trips. Different equipment have voltage sensitivity thresholds, and when voltage sags are below that specific threshold, they can lead to interruption of supply, and as a result, they will result in financial losses.

In this dissertation, the impact of distributed generation (DG) on voltage sag performance is investigated. Using a stochastic approach, voltage sag performance is assessed by using a method of fault position to determine profiles of magnitudes of remaining voltages at a monitoring point. From these, the expected number of critical voltage sags at a monitoring point are calculated, and the expected cost of these sags is derived for various voltage sensitivity threshold limits. An illustrative study is carried out comparing the voltage sag performance and expected costs of voltage sags for a network without DG and a DG Case for various mixes of customers.

It was shown that in the presence of DG, the expected number of critical voltage sags was lower for all voltage sensitivity criteria assumed and for all customer mixes. In addition, the expected costs of voltage sags were fewer for all voltage sensitivity criteria. This study has shown the positive impact of DG in improving the voltage sag performance and the expected cost of voltage sags.

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Chapter 1: Introduction

1.1. Overview of Quality of Supply

The objective of this chapter is to first introduce quality of supply as a global problem and later align it with a local problem called voltage sag. The definition of quality of supply will be covered first followed by interest in quality of supply. This section will close with the classification of quality of supply, where the problem of voltage sag will be introduced.

1.1.1 Definition of Quality of Supply

In the early years of supplying electricity to customers, reliability and quality were not main concerns, as industries were not yet developed. As the development of industries continues to grow, it becomes a real the issue of reliability and quality, as equipment experiences regular trips due to voltage disturbances. Customers were more concerned about this reliability and quality due to the development of power-dependent technologies such as computers and other sensitive equipment. Many utilities, thus far, can deliver reliable power to their customers.

The remaining element of acceptable voltage is the quality, which introduced this study to the term "Quality of Supply". Customers have become aware of the importance of quality of supply, especially those in process industries and sensitive equipment that cost a great deal of money when their processes are disturbed.

Electric Power Quality (EPQ) is a term that refers to maintaining the near-sinusoidal waveform of power distribution bus voltages and currents at rated magnitude and frequency [1]. Another definition of power quality—loosely defined—is the study of powering and grounding electronic systems so as to maintain the integrity of the power supplied to the system.

IEEE Standard 1159 [2] defines power quality as the concept of powering and grounding sensitive equipment in a manner that is suitable for the operation of that equipment. There is no single definition of quality of supply; therefore, it is a very wide definition, and it refers to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and at a given location on the power system.

"Quality of supply is the combination of current quality and voltage quality, involving the interaction between the system and the load. Voltage quality concerns the deviation of the voltage waveform from the ideal sinusoidal voltage of constant magnitude and constant frequency. Current quality is a complementary term, and it concerns the deviation of the current waveform from the ideal sinusoidal current of constant magnitude and constant frequency. Voltage quality involves the performance of the power system toward the load, while current quality involves the behavior of the load toward the power system [3].

QoS research has reached a considerable milestone since it received its first attention. In South Africa, a regulator requires various services and the minimum standards for measuring the quality of service provided to customers by electricity utilities. The regulator requires electrical utilities to report for evaluating quality of service when [4]:

- granting distribution licenses;
- monitoring the performance of licensees on an ongoing basis; and

- dealing with customer complaints.

The fact that this subject has been thoroughly considered in other studies does not necessarily mean that enough has been done, and it will be forgotten, but it will continue to deserve attention from both customers and utilities as technologies evolve. Since the utilities' renewable generation is integrated into the grid, the need to evaluate their impact on the grid quality of supply is on the rise, while on the customer side, vast equipment manufactured is becoming integrated and sensitive to voltage fluctuations.

1.1.2 Interest in Quality of Supply

The ultimate reason why there is an interest in power quality is because of its economic value. There are economic impacts on utilities, their customers, and suppliers of load equipment [5]. It can have a direct economic impact on many industrial consumers. The organization of the worldwide economy has evolved toward globalization, and the profit margins of many activities tend to decrease. The increased sensitivity of the vast majority of processes (industrial, services and even residential) to quality of power problems turns the availability of electric power, with quality being a crucial factor for competitiveness in every activity sector. The most critical areas are the continuous process industry and the information technology service [6].

Customers have become aware of economic losses that quality of power may cause in their businesses. Thus, even if there was no outage, some customers have sensitive equipment that may lead to failure and disconnection and, as a result, lead to loss of processes.

The general reasons for the increased interest in power quality can be summarized as follows [7]:

- Metering: Poor power quality can affect the accuracy of utility metering.
- Protective relays: Poor power quality can cause protective relays to malfunction.
- Downtime: Poor power quality can result in equipment downtime and/or damage, resulting in a loss of productivity.
- Cost: Poor power quality can result in increased costs due to the preceding effects.
- Electromagnetic compatibility: Poor power quality can result in problems with electromagnetic compatibility and noise.

Amongst other reasons, the reasons for interest in power quality are as follows [8]:

- Equipment has become more sensitive to voltage disturbances.
- Equipment causes voltage disturbances.
- A growing need for standardization and performance criteria.
- Utilities want to deliver a good product.
- Power supply has become too good.
- Power quality can be measured.

One crucial element in dealing with this electromagnetic phenomenon is to characterize it—the reason being that there are different ways to solve power quality problems, depending on the particular variation that is of concern. This electromagnetic phenomenon is caused by power system disturbances. It is therefore essential to team up both reliability and quality.

1.1.3 Quality of Supply Classifications

Power system disturbances are the major causes of poor quality of supply. The following are the classification of power system disturbances:

- interruption/under voltage/over voltage
- voltage/current unbalance
- harmonics
- transients
- voltage sag
- voltage swell
- flicker
- ringing waves
- outage

In this study, quality of supply is a general term for power system disturbances; however, it is restricted to one specific disturbance called voltage sag. The next section will introduce voltage sags.

1.2. Overview of Voltage Sag

In the previous section, quality of supply was introduced as the umbrella term, and voltage sag was introduced as one of its phenomena. This section will introduce the definition of voltage sag followed by why there is so much interest in this power quality phenomenon.

1.2.1 Definition of Voltage Sag

One of the most common power quality problems today is voltage sag. A voltage sag is a short time (10 ms to 1 min) event during which a reduction in root mean square (rms) voltage magnitude occurs [9].

A voltage sag is a sudden reduction in the rms voltage for a period of between 20 ms and 3 s of any or all of the phase voltages of a single-phase or a polyphase supply. The duration of a voltage dip is the time measured from the moment the rms voltage drops below 0.9 per unit of declared voltage to when the voltage rises above 0.9 per unit of declared voltage [10]. According to [3], a voltage sag is a decrease in rms voltage or current at the power frequency for a duration of 0.5 cycle to 1 minute.

In [8], voltage sag is defined as a voltage magnitude event with a magnitude between 10% and 90% of nominal and a duration of between 0.5 cycles and 1 minute or a voltage magnitude event with a magnitude less than the nominal voltage and a duration between

0.5 cycles and a few seconds. Sudden voltage sag in the supply voltage by a value of more than 100/0 of the reference value is followed by a voltage recovery after a short period of time.

1.2.2 Interest in Voltage Sag

The interest in voltage sags is because they cause the majority of equipment to trip. On the other hand, the starting of induction motors also leads to voltage sag. The main causes of voltage sags are faults or short circuits in the utility system, a fault within the customers' facility or a large increase of the load current, similar to starting a motor or transformer energizing voltage sags due to an induction motor starting lasting longer than those due to short circuits.

Typical durations of the aforementioned are seconds to tens of seconds. Equipment operates best when rms voltage is constant and equal to the nominal value, but when it is zero for a certain period, they stop immediately to operate. Voltage sags account for most interruptions of supply to customers. The main difference between voltage sag and interruption is that voltage sag is more of a global problem, while an interruption can be fixed by improvement on the feeder, whereas voltage sag will require improvement on several feeders.

The impact of voltage sag can only be explained by its effect on certain sensitive loads. Certain customers have manufacturing plants that involve many devices which are integrated together. If one of such devices fail, this can lead to the stoppage of the entire plant or process. On that account, that can lead to expensive loss of production. The following equipment is sensitive and has common effects of voltage sag [3]:

- IT and process control equipment
- contactors and asynchronous motors
- power drives

The most critical part of dealing with voltage sags is to appreciate the expected voltage sag performance of the supply system so that facilities can be designed and equipment specifications developed to ensure the optimum operation of production facilities especially to customers with sensitive loads. The following is a general procedure for working with industrial customers to ensure compatibility between the supply system characteristics and the facility operation [11]:

- Determine the number and characteristics of voltage sags that result from transmission system faults.
- Determine the number and characteristics of voltage sags that result from distribution system faults.
- Determine equipment sensitivity to voltage sags. This will determine the actual performance of the production process based on voltage sag performance calculated in steps 1 and 2.
- Evaluate the economics of different solutions that could improve the performance, either on the supply system (fewer voltage sags) or within the customer's facility (better immunity).

Quality of supply and voltage sag, as phenomena, were introduced in the previous sections. Both of them were covered in general. The next focal point of this dissertation is DG, which will be introduced in the next section. This will be introduced in general.

In this study, voltage sag is estimated stochastically. Quality of power disturbance can be categorized primarily into three categories [21]:

- production-related losses, such as loss of product/material, loss of production capacity;
- labor-related losses, such as employees, overtime, cleanup, and repair; and
- ancillary cost, such as damaged equipment, loss of opportunity cost and penalties.

The economic assessment of losses due to voltage sag specifically needs the following information:

- the number and characteristic of sags expected at a specified location over a period of interest;
- the information about the sensitivity of various types of equipment connected;
- the number of such equipment participating in an industry process along with its interconnection; and
- the information about the average cost claimed by different types of customers served at that point, attributed to a single trip of the process due to voltage sag.

The estimated number of trips for different voltage criteria due to a particular fault needs to be calculated first in order to estimate the cost of voltage sag. During the estimation of the cost, the above-mentioned information will be crucial to take into account.

1.3. Overview of Distributed Generation on Power System

Any power source that is directly connected to the distribution grid or end user system can be defined as DG [12]. In [13], conventional power stations, such as coal-fired, gas and nuclear-powered plants, as well as hydroelectric dams and large-scale solar power stations, are centralized and often require electricity to be transmitted over long distances. By contrast, DG systems are decentralized, modular and more flexible technologies that are located close to the load they serve, albeit having capacities of only 10 megawatts (MW) or less. They typically use renewable energy sources, including, but not limited to, small hydro, biomass, biogas, solar power, wind power, geothermal power and increasingly play a pivotal role in the electric power distribution system.

CIRED has a working group that devotes efforts to DG. It defines DG as all generation units with a maximum capacity of 50 MW to 100 MW, usually connected to the distribution network and neither centrally planned nor dispatched. On the other hand, the IEEE defines DG as the generation of electricity by facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in a power system [14].

Types of DG include the following:

- cogeneration
- solar power
- wind power
- hydropower
- waste-to-energy

A DG can have a positive and negative impact on a power system, depending on the type of technology of DG and at which location the network is located [14]. For example, large single-phase generators or many small single-phase generators will result in an increase in voltage unbalance. Synchronous machines are in general more advantageous than other types of interface, as their presence produce a voltage source that makes the distribution system stronger and introduces damping for these disturbances, especially during faults.

1.4. Objective of the Study

Certain types of DG, when connected to a power system, make a system to become stronger, which has a positive impact on voltage performance. This study investigates the impact of DG on voltage sag performance and further evaluates its economic impact. The next section will introduce the structure of the dissertation.

1.5. Structure of the Dissertation

Chapter 1 provides an introduction and background to the study.

Chapter 2 presents a literature review of existing literature on the stochastic estimation of the number of voltage sags. It will also cover the literature on the impact of DG on voltage sags performance.

Chapter 3 reviews the theory applicable in calculating the magnitude of voltage sags in a radial network, including the impact of a local generator. Estimated number of voltage sags are also covered in this chapter.

Chapter 4 presents the methodology for the case study. Stochastic estimation and cost will also be presented in this chapter.

Chapter 5 will provide the results and a discussion of the results.

In Chapter 6, conclusions will be drawn based on the above chapters.

1.6. Publication

During the course of undertaking this research, the following journal papers were submitted for review:

- N. Mbuli, R. M. Xezile, and J. H. C. Pretorius, "Impact of Distributed Synchronous Generation on the Stochastic Estimation of Voltage Sags."
- N. Mbuli, R. M. Xezile, and J. H. C. Pretorius, "Evaluation of the Impact of Distributed Generation on the Stochastic Estimation of Financial Costs of Voltage Sags."

Chapter 2: Review on DG and Stochastic Estimation of Voltage Sag

2.1. Introduction

The previous chapter introduced the concepts of quality of power and voltage sag and why there is so much interest in these subjects. The chapter also concluded by introducing DG and its impact on power systems. In this chapter, publications in voltage sag estimation and DG impact on voltage sag performance will be reviewed in order to evaluate what has been done on both subjects.

2.2. Stochastic Estimation of Number of Voltage Sags

To determine how a system performs from a voltage sag perspective, information about the expected number of voltage sags is critical. The most direct way of obtaining this information is by power quality monitoring. The drawbacks of this are that long periods are required if accuracy is to be reasonable; network changes can affect the credibility of results; and this method cannot be used to assess the performance of future networks. An alternative is to use probabilistic prediction methods to obtain the information, with the advantages that information on performance becomes available instantly, and performance of future networks can also be assessed.

A method for voltage sags stochastic assessment is presented in [15]. This method is based on exact analytical expressions derived from impedances of the Z-bus matrix and is totally opposite to the method of fault position, as it does not require a pre-assignation of discrete fault positions along the lines. The method that was developed was applied to a

24-bus system. The proposed formulation was found to be valid for all types of faults and can be applied to radial as well as to non-radial networks of any size.

In [16], an analytical expression for voltage sag magnitude at a bus due to faults at a random location on a transmission or distribution line is developed, analyzed and expressed. All types of faults and their effect on transformers were also incorporated into this analytical expression. The methods of critical distances, method of fault position and Mento Carlo method, which are generally used for stochastic assessment of voltage sag magnitude, were compared using these expressions. The number of fault positions was increased to a reasonable iteration in order to increase the resolution of accuracy. It was found that the method that directly and accurately provides the stochastic assessment of voltage sag magnitude is the method of critical distances. This method is simpler and easier to implement but requires a sufficiently large—yet unknown—number of fault positions and iterations respectively in order to converge to an acceptable solution.

The method of fault position was implemented to study the performance of voltage sags [17]. The simulation package used in performing the study was called PSCAD/EMTD. From simulation results, it was shown that three-phase faults caused stronger voltage sags as compared to the rest of the faults, and single-phase faults seldom cause any significant post-fault sags.

The method of fault positions was applied to predict an annual voltage sag frequency at a particular customer's site in the industrial estate [18]. The line parameters, substation bus, and operation of power system were considered in this study to determine the performance of voltage sags. The product area of the affected part at different percentages of voltage sag was used to calculate the annual expected number voltage sags. Both faults from transmission and distribution were considered and compared. The result of the study has shown that faults from distribution were often less than the ones caused by faults from transmission due to the characteristics of feeders in the industrial area.

A method that covers a large scope of financial losses by a single customer and network as a whole over a certain period of time due to interruption and voltage sag is presented in [19]. The methodology determines a prospective number of non-trips of an industrial process due to voltage sags. The precise counting of process trips is a primary part of the economic assessment of PQ, taking into account the quality of sensitive equipment behavior against voltage sags including all interconnection of equipment. Both the cost of voltage sag and interruption were separated and combined to estimate the annual total financial losses in the network.

The methodology in [19] was practically implemented in [20]. The methodology is illustrated on a general realistic distribution network with all relevant network components modeled appropriately. When there is no data, which happens many times in today's networks, the probabilistic approach was implemented, which leads to estimating the expected number of trips and financial losses. Both financial losses due to voltage sags and losses due to outages were compared and found to be in good agreement. Finally, identical network topologies were also compared, taking into account total financial losses in the network.

The estimation of financial loss due to voltage sags by the effect of transformer types is presented in [21]. Different types of transformers were calculated in a probabilistic manner for different types of load groups. Their effect on the system and their financial loss due to voltage sag were presented in [21]. The test system that was used was a nine-bus system. The simulation tool that was employed was called PSCAD/EMTDC software package. From the results, it was found that transformers have the greatest impact on the power system and hence on the financial loss due to voltage sags. Emphasis should be placed on their mitigation methodologies.

The effect of the transformer on the stochastic estimation of voltage sag was studied in [22]. Several stochastic methods for the estimation of number of sags have been developed in recent years. Various methods of sag prediction require lengthy programming or calculations. In this dissertation, the PSCAD/EMTDC software package was used to estimate the number of sags, assuming a uniform distribution of faults along the lines. It was found that simulation results of the system via PSCAD/EMTDC clearly indicate that the estimated number of sags experienced by the sensitive load at nodes under study is dependent on transformer type.

2.3. Impact of DG on Voltage Sag Performance

Despite the benefit of being environmentally friendly, DGs may be seen as a solution for many power quality problems, such as those related to voltage sags [12]. A study in [12] was conducted to evaluate the impact of DG on voltage sag magnitude and the frequency for a sensitive load. According to the results, the level of DG next to a sensitive end user influences the total number of voltage sags and the number of voltage sags classified by classes of magnitude. The computational tools that were used to make a simulation were ANAFAS and MATLAB. A Brazillian network was used in the case study.

In [23], the impact of DG on voltage sag performance was presented. Sixty-two case studies were carried out to evaluate phase-to-ground type of fault on transmission lines, and sensitive load bus was monitored. For each case, different fault positions were considered using different penetration of DGs. The method used to evaluate these studies was Monte Carlo. The software tools used to conduct the studies were ANAFAS-GUI and MATLAB. From the result of the studies, it was found that DG has an influence on the number of voltage sags.

The penetration of DGs has an influence on voltage sag, which was evaluated using IEEE-13 bus [24]. The software tool used in conducting the studies was MATLAB using ATP/EMTP. It was shown from the results of the study that the presence of DG has a positive influence on voltage sag performance. Also, DG on the downstream was performing better than DG on the upward stream.

The paper in [25] has explored the impact of a synchronous generator on voltage sag using a case study of small distribution network. The study was carried out using an ITIC curve. According to the results of the study, DG has a positive impact on voltage sag performance if the fault duration is not longer than 2s.

The paper in [26] investigated the impact of three technologies, namely, the converter base DG, synchronous and asynchronous generators on voltage sag in low distribution grid. It was found that the impact of voltage sag on low-voltage networks was minimal, while the converter base has the same effect; however, the converter base was able to mitigate most sags on the connected equipment terminals. The converter base did not perform well at transmission level.

The most important economic benefits by DG technologies were realized in distribution utilities as illustrated in [27]. Models were produced to identify those benefits and were translated into economic terms. Industry, regulators or utilities were charging owners of DGs connection fees, while on the other side they were saving significant amounts for utilities. This document has realized benefits of integrating DG into the network by quantifying them into economic terms.

In [28], the results and analysis of integration requirement for the Concentrating Solar Plant (CSP) are presented in this paper. In South Africa, a place called Upington is characterized by much sunlight throughout the year and is viewed as a hot area. Its network, where the CSP is planned, is a very weak network that has long lines supplying loads located remotely from the main network. The paper performed loadflows analysis, short circuit studies and transient stability studies to evaluate the impact of connecting a CSP plant. The software tool used for studies was PSS/E. The paper compared a base case with a case having a CSP plant. According to the results, a CSP plant increases the fault levels and has a reduced impact of voltage sags.

Finding the best configuration and DG capacity in a distribution system for minimizing voltage sag was investigated by [29]. The software tool that was used to run the studies was MATLAB. All four scenarios were considered and compared. Simulation results showed that a case with DG can improve voltage sag index by 75%. The type of fault considered was a three-phase fault.

The aforementioned work was further extended by [30]. Instead of considering a single plant of 50 MW X 1, 50 MW X 2 and 50 MW X 3 were considered in the paper. Again, the software tool used to perform the studies was PSS/E. From the results of this paper, despite improving network capacity, DG plants can strengthen the weak distribution network by reducing the severity of voltage sags.

A study was conducted to assess the severity of a voltage sag at a particular power station [31] before and after commissioning a CSP plant. A three-phase transmission fault recorded historically was simulated. The objective of the study was to first tune the simulation to match the recorded fault and secondly build two cases, namely, base case and a case with CSP plant and compare the results. According to the results, the CSP plant led to a substantial improvement in the severity of voltage sags recorded.

In [8], a DG is modeled as a local generator connected to the distribution network. The illustration indicated that it mitigates voltage sags of the load in two different ways. First, the generator increases the fault levels at the bus of interest, and as a result, it reduces the severity of voltage sags with the rest of the system. Secondly, the generator increases the voltage at a local bus by feeding into the fault. If the generator is not present, the voltage at the equipment terminals will be equal to the voltage at the PCC.

A small-scale distributed generator connected to a low-voltage network through a control converter to improve voltage is investigated in [32]. The software used to model the converter was MATLAB and SimPowerSystems. It was found that the proposed scheme can improve the voltage by mitigating voltage sags both at transmission level and distribution level.

A case study was conducted by [33]. The system of study used is a Belgian medium-voltage distribution network. The type of study was power quality and voltage stability with different DG technologies. In the study, it was found that, generally, DG can improve and support the voltage profile of the distribution system. The study has indicated that DG strongly supports the voltage stability at nearby nodes and has less impact on distant ones.

Voltage control of DGs plays a very critical role in improving the reliability of distribution networks. Although uncontrolled generation reduces losses, the ability to control the output of a generator for improving the voltage sag performance is significantly greater than that of an uncontrolled generator. By using a good set of rules including optimization, change in voltage like voltage sags can be mitigated [34]. The study has shown the benefits of using DG to improve network performance, especially when considering controlled generation against uncontrolled generation.

A method that compares the performance of a protection system is investigated in [35]. In this paper, the impact of DG on voltage sag performance using a small test distribution network is presented. It was found after carrying out the study that, indeed, DG has a positive effect on the performance of voltage sags for a fault duration that is less than 2s. It was also found that DG maintains the voltage to healthy phases during the fault.

In contrast with the positive effect on the voltage performance by helping to keep the during-fault voltages, a study was conducted in [36]. This study presents a voltage control method to increase DG transfer capability and to ensure distribution network voltage within statutory limits. A simulation was carried out using PSS/Adept software. According to [36], the introduction of DG caused the voltage to rise at PCC, leading to customers' voltages being out of the allowable range.

2.4. Conclusion

Based on the literature review in this chapter, much work has been covered on stochastic estimation of number of voltage sags. There are three methods of stochastic estimation of number of voltage sags, namely, Monte Carlo method, method of critical position and method of fault position. The most accurate method is the method of fault position, while the Monte Carlo and method of critical position requires a sufficiently large number of fault positions. Most of these methods require well-known software tools that include MATLAB and PSCAD.

The literature also covered the impact of DG on voltage sag performance. DG, in most of the cases, is associated with renewable energy sources; hence, they have the benefit of being environmentally friendly. Despite this fact, they have another added benefit of generally having a positive effect on the voltage sag performance of distribution networks; as a result, they mitigate voltage sags.

In this study, the results of a study into the impact of DG on the expected cost of voltage sags will be presented. The voltage sag performance of the power system is determined using the stochastic method of fault positions. From this, the expected number of critical voltage sags will be determined. Finally, the expected cost of voltage sags will be calculated for various customer mixes, and they are then compared for case without DG and for DG Case.

Chapter 3: Theory of Techno-Economic Impact of DG on Voltage Sags

3.1. Introduction

The foregoing chapter was a literature review on the stochastic estimation of voltage sags and the impact of DG on voltage sag performance. This chapter will introduce the theory of voltage sag magnitude in a radial system in general followed by inclusion of DG. Calculating the expected number of critical sags will also be covered in this chapter. Finally, calculations of the expected cost of voltage sags will also be presented.

3.2. Voltage Sag Magnitude in Radial System

As stated from the above introduction, voltage sag magnitude will be expressed in radial system. To quantify voltage sag magnitude, the voltage divider model is used [8]. This is used in the radial system. The circuit shown in *Fig. 1* represents a radial network with a sensitive load located at PCC. By applying the voltage divider rule or Kirchoff's rule after the fault experience, as illustrated in the figure, the expression of voltage at PCC can be expressed as follows:

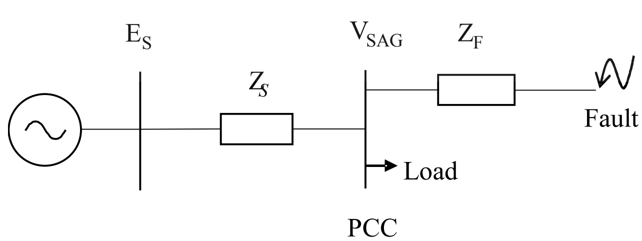

Fig. 1: Radial network supplying a sensitive load.

The voltage at PCC can be expressed as follows:

$$V_{SAG} = \frac{Z_F}{Z_F + Z_S} E_S$$

where

V_{SAG} = The voltage at PCC and, thus, the voltage at the equipment terminals

Z_F = The impedance between the point of common coupling and the fault

Z_S = Source impedance at the point of common coupling

E_S = Source voltage

If the pre-fault voltage is equal to unity, e.g. $E_S = 1$ p.u. from the above-mentioned equation, then it can be expressed as follows:

$$V_{SAG} = \frac{Z_F}{Z_F + Z_S} \quad (1)$$

Assume that there is no voltage drop between the load and the PCC. Any fault impedance should be included in the feeder impedance Z_F. It can be noted that as Z_F becomes smaller, the value of V_{SAG} becomes very small, meaning that voltage sag becomes deeper for faults electrically closer to the load or the customer as illustrated in (1). *Fig. 2* illustrates sag magnitude as a function of distance to the fault in general.

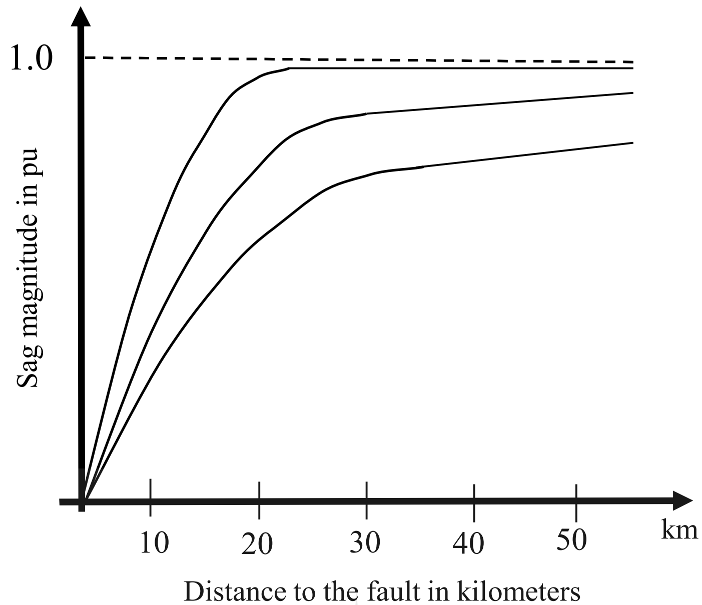

Fig. 2: Sag magnitude as a function of distance.

3.3. The Inclusion of Local Generator (DG) on Voltage Sag Performance

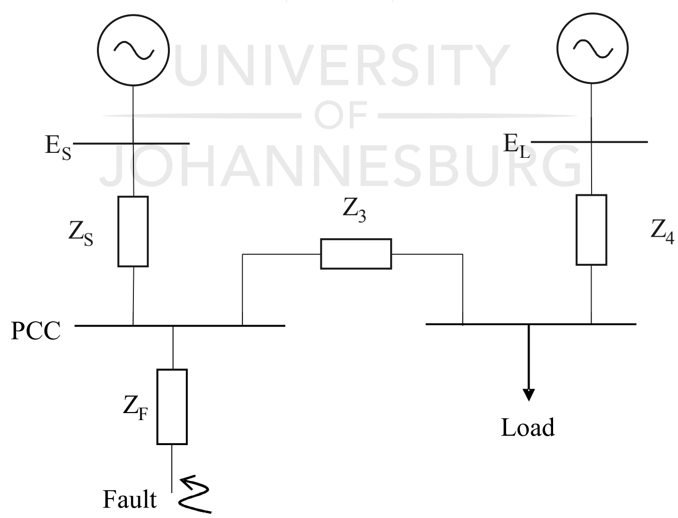

Fig. 3: Equivalent circuit for calculating voltage sag when DG is incorporated.

When the local generator is not feeding to the point of common coupling, the expression of voltage sag with the inclusion of a local generator as illustrated in *Fig. 3* is given by the following:

$$V_{SAG} = 1 - \left[\frac{Z_4}{Z_3 + Z_4} \left(1 - V_{PCC}\right) \right] \tag{2}$$

The improvement in voltage level can also be inferred from the fact that even if the voltage at the PCC drops to zero (0), the magnitude of the voltage sag at the customer, $V_{sag(min)}$, can be expressed by equation (3) and is never zero (0).

If the voltage at the point of common coupling is zero, $V_{pcc} = 0$, then voltage sag will be given by equation (3) signaling that it will never be equal to zero.

The inclusion of a local generator has demonstrated the following:

- Improvement of short circuit strength
- Severity of voltage sags reduced.

$$V_{sag(min)} = \frac{Z_3}{Z_3 + Z_4} \tag{3}$$

Over and above (2), increasing short circuit strength of networks are realized, thereby helping to decrease the severity of voltage sags. DG also maintains voltages during faults by feeding into faults, thus improving voltage sags performance.

3.4. Estimating the Expected Number of Critical Voltage Sags

As stated in Chapter 2, the method of fault position gives a better estimation as compared to other methods, as it involves selecting a number of discrete positions along lines that are placed at equal distances. Thereafter, faults are applied at these positions, and the magnitude of the remaining voltage at each position is recorded. A large number of positions is chosen in order to increase the accuracy of results. To demonstrate the method of fault position, *Fig. 4* will be used. Within power system, an area between busses *p* and *q* is considered [15].

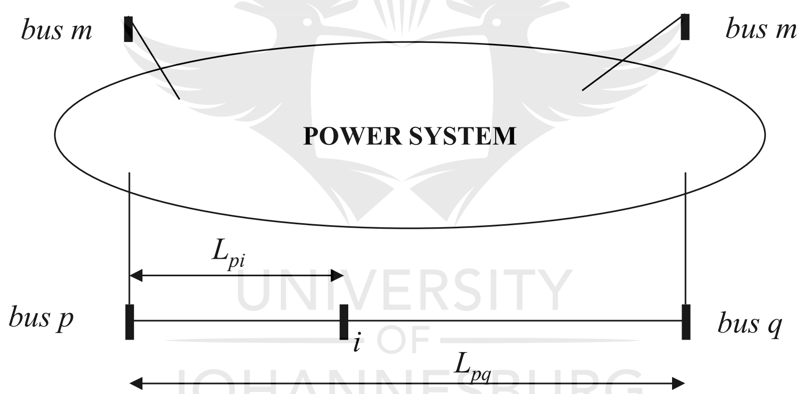

Fig. 4: Single line diagram to demonstrate power system, with a line between busses p and q shown [15].

When a fault takes place along the line *pq,* which has a range 0 to 1 ,this fault is identified by the parameter φ. This parameter will represent the location on the line at which a fault occurs. The expression of the probability that the fault will occur between 0 to 1 is given by equation (4) as follows:

$$\varphi = \frac{L_{pi}}{L_{pq}} \tag{4}$$

where L_{pi} is the distance of the fault position from bus *p,* and L_{pq} is the total length of the line. Furthermore, *m* is the customer location at which voltage sag performance is to be monitored (i.e. monitoring location). A graph as shown in *Fig. 5* can be used to depict the function V^a_m (Ψ). The aim is to calculate the movement of voltage sag on the faulted phase against the faulted position, *i*, on line *p*-*q*.

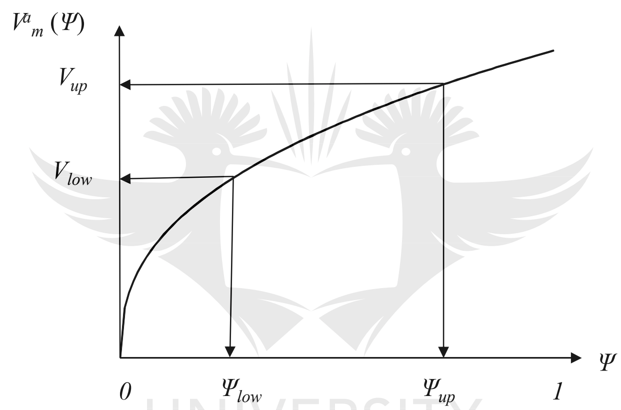

Fig. 5: Magnitude of voltage recorded at monitoring point as the fault position moves along the line.

Therefore, the voltage will vary as a function of Ψ and can be plotted as illustrated in the *Fig. 5*. From the graph above, it can be noted that the voltage sag V_{low} and V_{up} is exactly equal to the probability of fault occurring between Ψ_{low} and Ψ_{up} respectively. The expression of a probability can be the following:

$$P\left(V_{low} \leq V^a_m(\Psi) \leq V_{up}\right) = P\left(l_{low} \leq l \leq l_{up}\right) = \int_{\Psi_{low}}^{\Psi_{up}} f\left(l\right)dl \tag{5}$$

Where

$P(V_{low} \leq V \leq V_{up})$ is the probability that the voltage sag at point m is between V_{low} and V_{up},

$P(\Psi_{low} \leq \Psi \leq \Psi_{up})$ is the probability that a short circuit occurs between Ψ_{low} and Ψ_{up}, and f(l) is the probability distribution function of faults, with l and v in per unit.

The sequence events of fault occurring along the transmission line are not predictable and easy to estimate. They are stochastic and can only be evaluated using probability. The following are causes of transmission faults [37,38,39] :

- trees
- animals
- equipment failures
- fires and
- accidents that damage line infrastructure.

If a probability of a fault occurring per annum along a transmission line is known, it can then be substituted in equation (5) so that the probability of fault occurring between two location can be determined.

Consider the probability is a random variable name Y, let its probability density function called *f(y)*, is known [40], then the probability that the random variable lies between y1 and y2 can be written as

$$P(y_1 \leq Y \leq y_2) = \int_{y_1}^{y_2} f(y)dy \tag{6}$$

If a uniform probability density function is assumed for faults occurring in this system, equation (6) can be rewritten [40] as

$$\begin{aligned} P\left(V_{low} \leq V_m^a(\Psi) \leq V_{up}\right) = P\left(l_{low} \leq l \leq l_{up}\right) &= \int_{\Psi_{low}}^{\Psi_{up}} 1dl \\ &= \Psi_{up} - \Psi_{low} \end{aligned} \tag{7}$$

Assuming Y is a continuous variable with a uniform probability distribution then Y can be written and derived as illustrated in equation (8).

$$F(y) = \int_{\theta_1}^{\theta_2} f(y) = \int_{\theta_1}^{\theta_2} \frac{1}{\theta_2 - \theta_1} d\theta = 1 \tag{8}$$

It is a clear from equation (7) that voltage sag per annum can be estimated if the number of faults over the same period is known. That can be easily done once historical faults statistics is known. Let the faults per annum for a line be λ_q ,The number of voltage sags at node m be between V_{low} to V_{up}, then the number of voltage sags can be expressed as equation (9):

$$N_q^a\left(V_{low} \leq V_m^a(\Psi) \leq V_{up}\right) = \lambda_q\left(\Psi_{up} - \Psi_{low}\right) \tag{9}$$

When equipment is bought from equipment manufacturers, certain organization around the world made available standards and grid codes in which equipment must meet. Manufactures will produce such equipment meeting such standards. It will then be easy when connecting such equipment at a particular point, information about the number of trips will be possible to determine using equation (9) provided that λ_q is known, which is usually the historical fault data of a particular performance of a line[11,41].

Usually, the information required on a voltage sag study is the expected number of voltage sags per year (sags/year), at the system busses, typically indicated within a selected range of sag magnitude.

3.5. Calculating Expected Cost of Voltage Sags

Now that the expected number of voltage sags was expressed in equation (9), the next step will be to calculate the estimated cost of voltage sags. The approach for calculating the estimated cost of voltage sags due to single phase-to-ground faults, the following expression is used in equation (10) [21]:

$$N_{1\phi-crit} = \sum_{j}^{m}\left(l_j * \lambda_q * p_{1\phi}\right) * \rho_{sag(j)} \tag{10}$$

where

$N_{1\phi\text{-}crit}$ is the number of critical voltage sags recorded at bus 1

l_j is the length of line j

m is the number of lines in the system

λ_q is the number of faults/km/annum for the network

$p_{1\phi}$ is the fraction of single phase-to-ground faults,

translating to the probability of such faults

$\rho_{sag(j)}$ is the probability of a voltage sag at bus 1 due to a fault on line i

After expressing the number of critical voltage sags, the next step would be to express the cost of voltage sags due to single-phase-ground using the next equation (11).

$$R_{1\phi} = N_{1\phi-crit}\left[\sum_{i}^{n}\left(p_i * c_{sag(i)} * p_{1\phi} * c_{operate(i)}\right)\right] * c_{severity} \tag{11}$$

where

$R_{1\phi}$ is the cost of voltage sags per annum of customers connected to a monitoring point of interest due to critical voltage sags caused by faults in the power system

N_{cr} is the number of critical voltage sags recorded at monitoring point due to faults in the power system

p_i is the percentage of load that is of type i (e.g. industrial, commercial, and residential)

$c_{sag(i)}$ is the estimated cost per voltage sag for customer of type i

$c_{operate(i)}$ is the correction factor for duration of operation, representing fraction of time that customer type i is running its operations

$c_{severity}$ is the scaling factor for severity of voltage sag, with a very low scaling factor for less severe sags

3.6. Conclusion

In this chapter, the theory that supports the determination of voltage sag magnitude was examined. It described how to calculate the magnitude of voltage sag magnitude from the theoretical radial system. The impact of a local generator was also expressed. From theory, the generator increases the voltage at PCC. Voltage sag expression in a meshed network was also considered. The chapter was able to express the magnitude of remaining voltage in faulted phase in unbalanced faults. Therefore, this expression will have to appreciate the results from case study. Finally, this chapter closes with the expression of stochastic estimation of voltage sag expression together with estimated cost expression. Therefore, this expression will be used in the next chapter to stochastically estimate and calculate the cost associated with voltage sags.

The next chapter will describe the methodology that is going to be applied to the test system, and the results will also be presented.

Chapter 4: Methodology of the Study and Case Study

4.1. Introduction

The preceding chapter described the review of the theory associated with voltage sag in a radial and meshed system. The theory of stochastic voltage estimation was also covered. In this chapter, the methodology of the study will discuss in detail how the study was conducted. The case study will be presented including data used.

4.2. Case Study: Description of the Methodology

In this section, all information of the case study done to assess the impact of distributed generation on the expected number of voltage sags are first described. Then the results of the voltage sag profiles will be presented. Software package PSS/E [42] was used to conduct studies. The study system used will also be presented in this section. Details of the assumed data will be described and presented, while procedures to conduct simulations will also be discussed.

The single-line diagram of the study system is illustrated in *Fig. 6.* Six critical industrial customers are connected at six nodes of the same 20 kV distribution line (40 km total length) through a solidly grounded delta-wye transformer as illustrated in the figure.

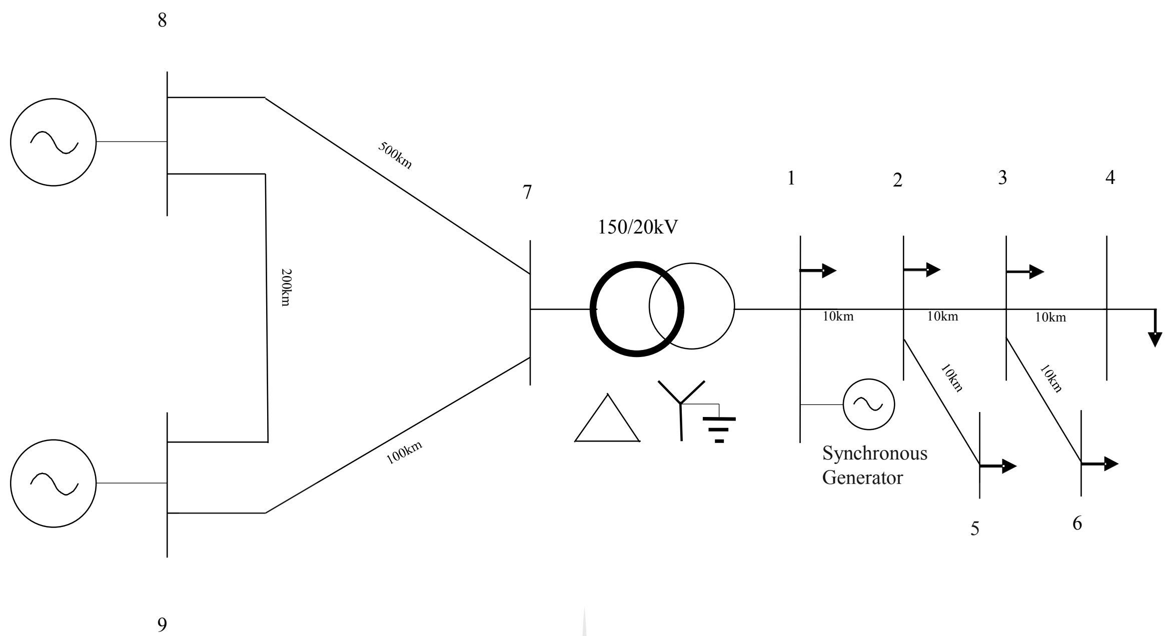

Fig. 6: Single-line diagram of 9-bus system [21].

From the secondary of the transformer, all busses are staged to equal distances of 10 km with a voltage sitting at 20 kV. The equivalent transmission system consists of three 150 kV lines and is relatively of a large size of 800 km total length. From bus 7 to bus 8, the distance is 500 km; from bus 8 to bus 9, the distance is 200 km; and from bus 9 to bus 7, the distance is 100 km. All the loads were identical at 1.07 MW and 0.1 MVar. The line parameters used in the study area are all presented in *Table* 1

Bus 8 is the system's swing bus. For the case with the distributed generator, a steam turbine generator is connected to bus 1. For representing dynamics in the system, the PSS/E round rotor machine model, GENROU, is used. For the exciter, the model IEEET2 is utilized.

Table 1: Transmission and distribution line data used in the study.

Busses i-j	Positive & Negative Sequence Data (Ω per unit/km)	Line Charging (S per unit /km)	Zero Sequence Data (Ω per unit/km)
1-2, 2-3, 3-4	0.22+j0.37	0.003000	0.37+j1.56
2-5, 3-6	1.26+j0.42	0.001000	1.37+j1.067
7-8, 8-9, 7-9	0.097+j0.39	0.010000	0.497+j2.349

Table 2: Rated and output generator data used in the study.

Generator Bus	MW (rated)	MW (output)	MVar (rated)	MVar (output)
8	10	3.7	10	2.2
9	10	3.0	10	3.8

Table 2 summarizes the data for the generators used in the study. In modelling the synchronous generator in these studies, a round rotor generator model which is found in PSSE library models was assumed. This model is suitable for steam turbine generators. A sub-transient reactance of 0.12 per unit was also assumed, which is a characterized value for turbo generators of that size [43]. The excitation system assumed was the IEEET2 system which is also found in PSSE library. For simplicity, power system stabilizers were not used in these studies.

4.3. Preparation of the Dynamic Case File

The first step of performing studies was to prepare a loadflow case file to give reasonable voltages and power flows in order to reduce the possibility of wrong results in steady state before performing dynamic studies. The process can be briefly summarized as follows:

- Prepare the case file in order to ensure the loadflow solves properly such that no loading of lines and voltage constraints
- Call the dynamic data to ensure that the system starts without any errors
- Run the system in dynamics without applying a fault to confirm that steady state voltages correspond with dynamics voltages
- After 0.05s apply a fault. During that time, replace transmission line with equivalent model of a line that was recorded in steady state. The exact location of the line will match with the parameters of the line model.
- The magnitude of the remaining voltage will then be recorded for that fault
- Studies were repeated for every 5% length of the line. All types of faults were considered.

The next chapter will provide results of the study and a discussion of the results.

Chapter 5: Results and Discussion

5.1. Introduction

The previous chapter considered the methodology employed in this study. In this penultimate chapter, simulation results of voltage sag profiles for all lines from the study area will be presented. The summary of the distribution of voltage sags will follow. The expected number of critical voltage will also be presented. Finally, the estimated cost of voltage sags will be presented in this chapter.

5.2. Case Study Results

The following were types of faults applied for every 5% of the length of all lines:

- single phase-to-ground fault (pg)
- phase-to-phase fault (pp)
- phase-to-phase-to-ground fault (ppg)
- three-phase fault (3p)

The approach used involves running transient stability studies to determine the magnitude of voltage sag at a point where performance is being assessed. The analyses of plots of the remaining voltages are shown next.

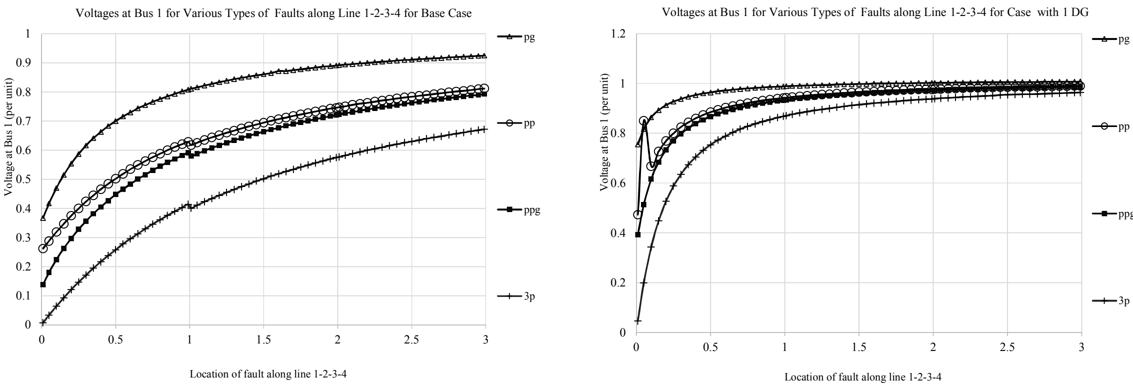

Fig. 7: Magnitude of voltage sag on the faulted phase recorded at bus 1 for faults on line 1-2-3-4 for Base Case and DG Case.

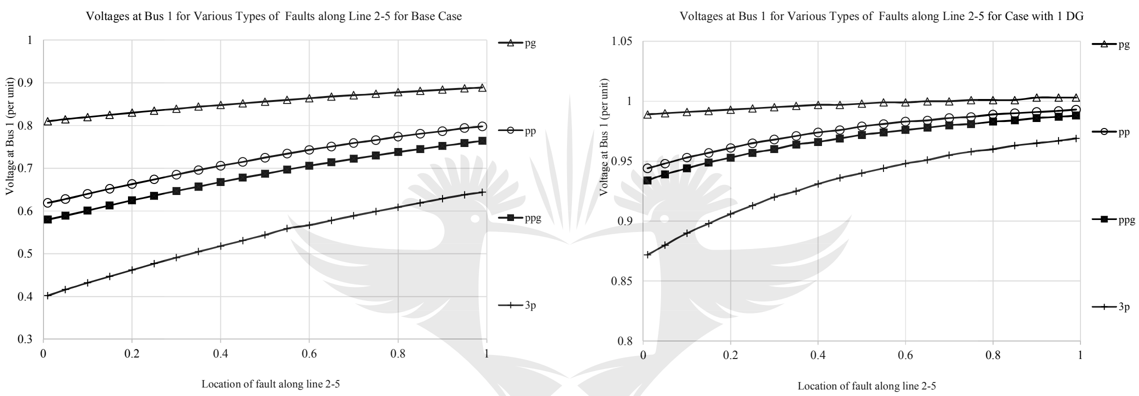

Fig. 8: Magnitude of voltage sag on the faulted phase recorded at bus 1 for faults on line 2-5 for Base Case and DG Case.

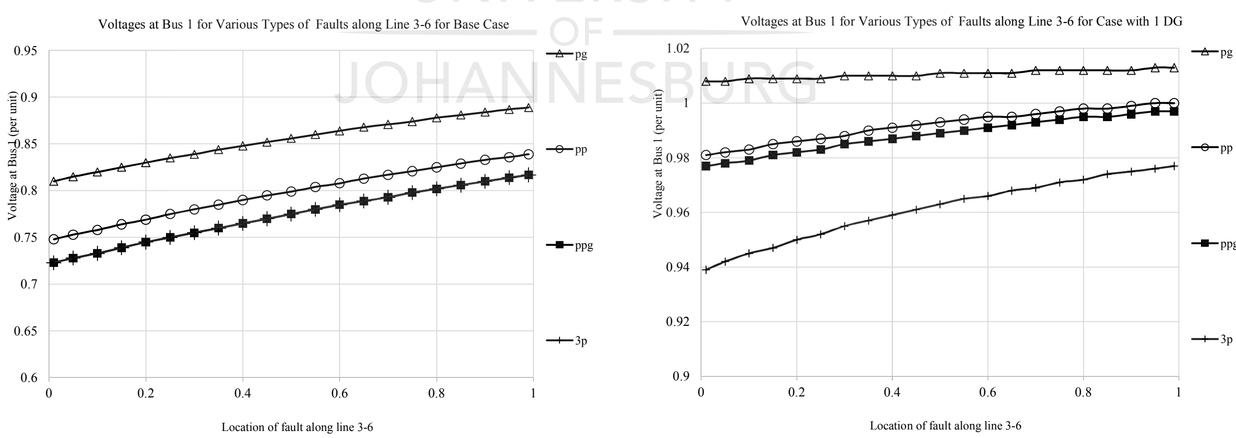

Fig. 9: Magnitude of voltage sag on the faulted phase recorded at bus 1 for faults on line 3-6 for Base Case and DG Case.

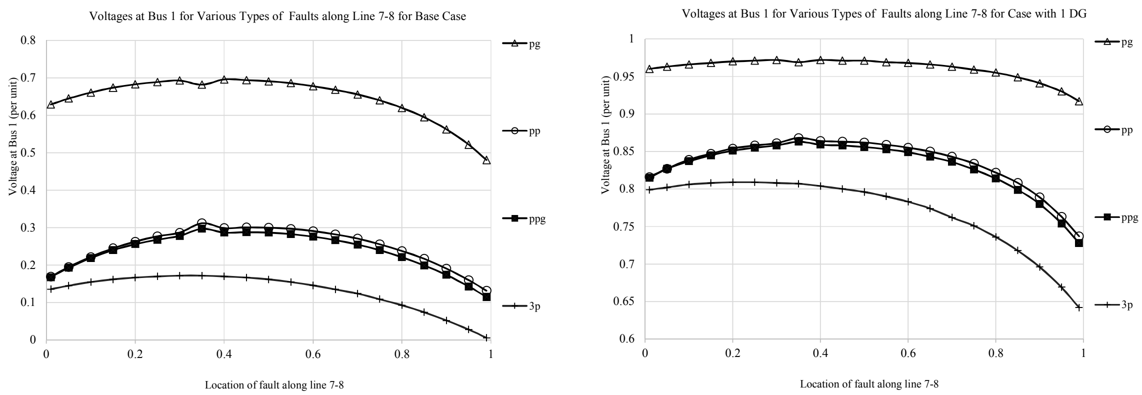

Fig. 10: Magnitude of voltage sag on the faulted phase recorded at bus 1 for faults on line 7-8 for Base Case and DG Case.

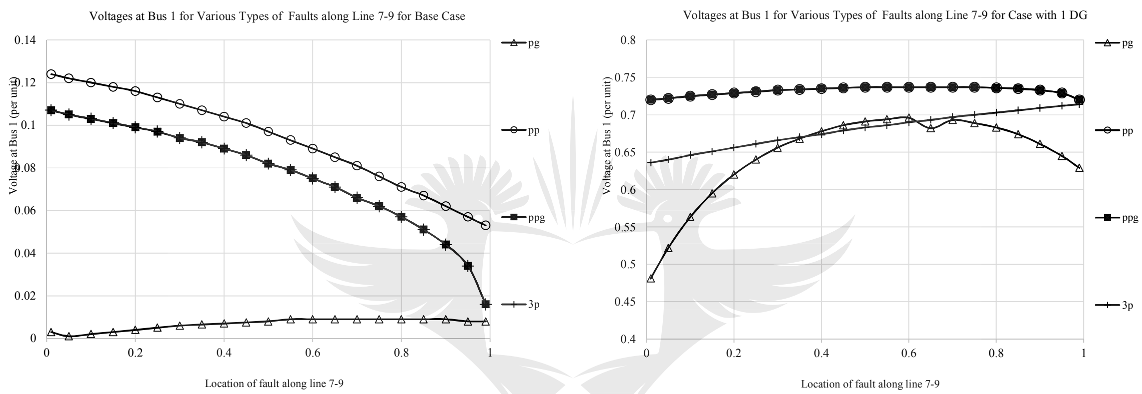

Fig. 11: Magnitude of voltage sag on the faulted phase recorded at bus 1 for faults on line 7-9 for Base Case and DG Case.

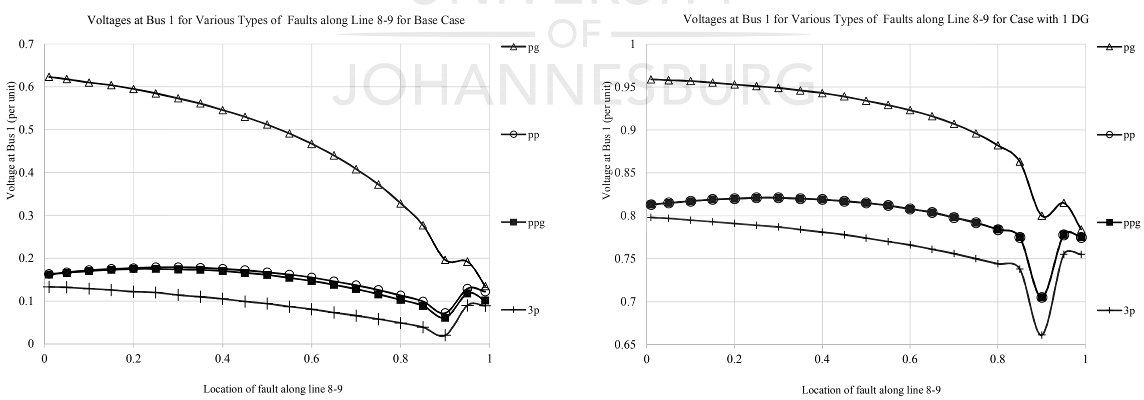

Fig. 12: Magnitude of voltage sag on the faulted phase recorded at bus 1 for faults on line 8-9 for Base Case and DG Case.

The approach is to evaluate the impact of DG on the remaining voltage on the faulted phase and compare it with the case without a DG. In this case, the monitoring point is at bus 1 and faults are applied at each and every 5% of the lines. There are two columns of the graphs from *Fig. 7 to Fig. 12*. The left-hand side graphs represent the Base Case, while the right-hand side graphs represent the case with DG. From the graphs, the following was observed:

- Three-phase faults in the radial line have a worse magnitude of the remaining voltage as compared to other fault types.
- Single-phase fault has better performance of the magnitude of the remaining voltage as compared to other fault types in the radial network.
- In all the cases above, a case with DG, the magnitude of the remaining voltage is mitigated as compared to the case without a DG (Base Case).

Therefore the above results have demonstrated that by integrating DG, it reduces the severity of voltage sags for all types of faults. There is an agreement with the literature that DG has a positive impact on voltage sag performance.

5.3. Summary of Distribution of Voltage Sags

The impact of DG in reducing the severity of some voltage sags is also illustrated in *Fig. 13*. The figure illustrates the probability distribution of voltage sags of all fault types which looks at the bigger picture.

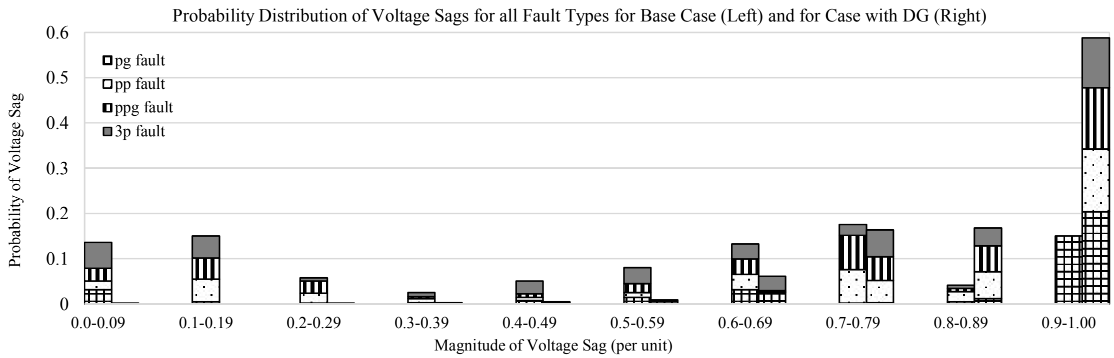

Fig. 13: Arrangement voltage sags for case without DG and DG Case.

From the *Fig. 13*, the following is observed:

- Single-phase fault has a high probability of magnitude of the remaining voltage on the band of 0.9-1.00pu, which indicates that of all types of faults, single-phase fault has less severe voltage sag than other types of faults in both cases.
- Three-phase fault is dominant in lower bands of the magnitude of the remaining voltage in Base Case as compared to all faults, which indicates that three-phase faults have severe voltage sags as compared to all types of faults.
- Case with DG shifted the probability of all types of faults to more dominant in the magnitude of the remaining voltage band 0.9-1.00pu. This indicates that the severity of voltage sag was indeed reduced.

5.4. Expected Number of Critical Voltage Sags

In the previous sections, the impact of DG on voltage sag performance was evaluated, and improvement of the magnitude of the remaining voltage was evident on the faulted phase for all types of fault. Also, the probability distribution of voltage sags was improved in the case of DG with respect to Base Case. When the customer intends to connect the sensitive load, it is required to have information on the number of voltage sags of a particular magnitude when the fault takes place. This information is needed for planning purposes; hence, during that time, it is impossible for the utility to measure the quality of supply on each and every busbar. The only way to get such information is to apply stochastic estimation, which uses the assumption of uniform distribution of probability of fault on the lines. The method has the advantage of giving answers now as compared to measuring power quality parameters, as it will take even years to get direct answers.

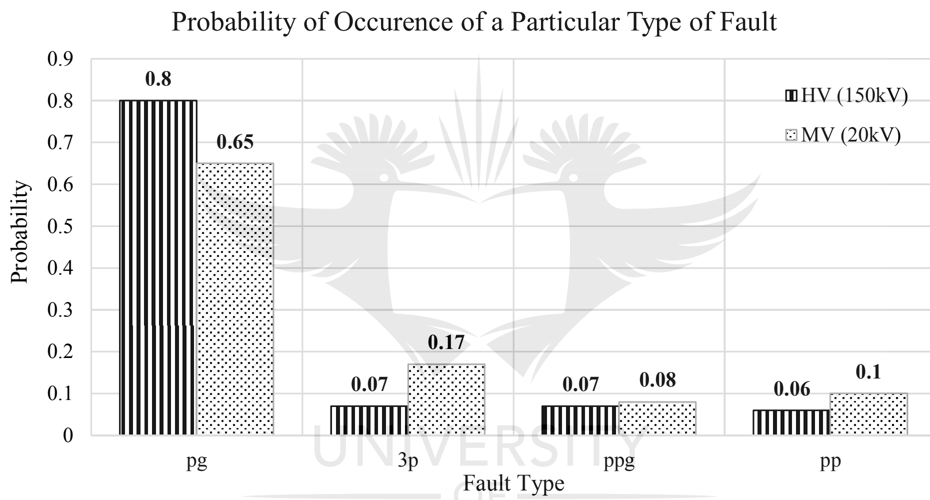

Fig. 14: Fault rate for various fault types for lines of 20 kV and 150 kV voltage levels.

Stochastic estimation is made by several assumptions which include several parameters. One of such parameters is the fault rate. This parameter is linked to the network analysis and historic fault statistic data. Several utilities have this type of data. The rates of fault occurrence used in calculating the number of faults on 20 kV and 150 kV lines are (1) and (0.1) fault/km/annum respectively. To estimate the number of voltage sags, the probability of a fault at a particular study system is critical. This parameter considers all types of faults on that particular system. For the purpose of this study, the probabilities of occurrence of various fault types are illustrated in *Fig. 14* for the two voltage levels in the network used. From the figure, it is observed that single-phase faults have a large probability of occurrence as compared to other types of faults. This historical data is a critical factor in estimating the number of voltage sags. The procedure for calculating the total number of voltage sags at bus 1 due to single phase-to-ground faults in the system can be encapsulated by (10). $N_{1\phi-crit} = \sum_{j}^{m} \left(l_j * \lambda_q * p_{1\phi} \right) * \rho_{sag(j)}$

(10

Certain loads will fail when the remaining voltage magnitude reach a particular value. For example, when the remaining voltage magnitude reaches 0.7 per unit voltage, certain motors will stop working. This voltage is a critical voltage criterion. In this study, there are three critical voltage criteria considered, namely, 0.6, 0.7 and 0.8 per unit voltage. The objective is to evaluate the impact of DG on the expected number of faults using these voltages as criteria. To illustrate this, a voltage criterion of 0.6 per unit kV is used

$$N_{1\phi-crit} = \sum_{j}^{m} \left(l_j * \lambda_q * p_{1\phi} \right) * \rho_{sag(j)}$$

(10. This is illustrated in

Table 3.

To explain the table, the first column is voltage levels, the second column is lines, and the third column is a fraction of voltage sags taken from voltage profiles which are below 0.6 p.u. The fourth column is a length of the lines. The fifth column is the length of the line multiplied by the fault rate used for 150 kV. The sixth column is the value in column fifth multiplied by the probability of fault due to a single phase as illustrated in *Fig.* 14. The seventh column is sixth column multiplied by the third column. The last column is the addition of all columns to get the total number of critical voltage sags due to single-phase fault on voltage criterion of 0.6 pu for Base Case.

Table 3: Calculation of the number of critical voltage sags for a single-phase fault and a critical voltage of 0.6 per unit kV.

Type of Fault	**Voltage Level**	**Name of a Line**	**Fraction of Voltage Sags, $\rho_{sag(i)}$**	**Length of Line (km), l_i**	**Expected Number of Faults on Line *i* per Annum**	**Expected Number of Single-phase faults on Line *i* per Annum**	**Expected Number of Sags per Annum Due to Single-phase faults on Line *i***	**Total Number of Critical Voltage sags due to Single-phase faults, $N_{1\phi}$**
Single-Phase-to-Ground	150kV	Line [7-8]	0.190	500	50.00	40.00	7.62	30.43
	150kV	Line [7-9]	1.000	100	10.00	8.00	8.00	
	150kV	Line [8-9]	0.810	200	20.00	16.00	12.95	
	20kV	Line [1-2-3-4]	0.095	30	30.00	19.50	1.86	
	20kV	Line [2-5]	0.000	5	5.00	3.25	0.00	
	20kV	Line [3-6]	0.000	5	5.00	3.25	0.00	

The illustration was only for a single phase for 0.6 per unit voltage on a base case. To calculate the expected number of critical voltage sags for various voltage criteria and for different fault types for Base Case and for the case with DG, a summary is provided graphically in *Fig. 15*.

From the graphs, the following is observed:

- As the voltage criteria are increased, the number of critical voltage sags increase for all types of faults.

- Single-phase fault recorded a large number of critical voltage sags as compared to other types of faults due to a high probability of single-phase faults as illustrated in *Fig. 14*.

- Phase-to-phase fault has recorded a low number of critical voltage sags as compared to other faults, which is due to their low probability contribution as illustrated in *Fig. 14*.

- Case with DG decreases the number of critical voltage sags as compared to the Base Case for all types of faults.

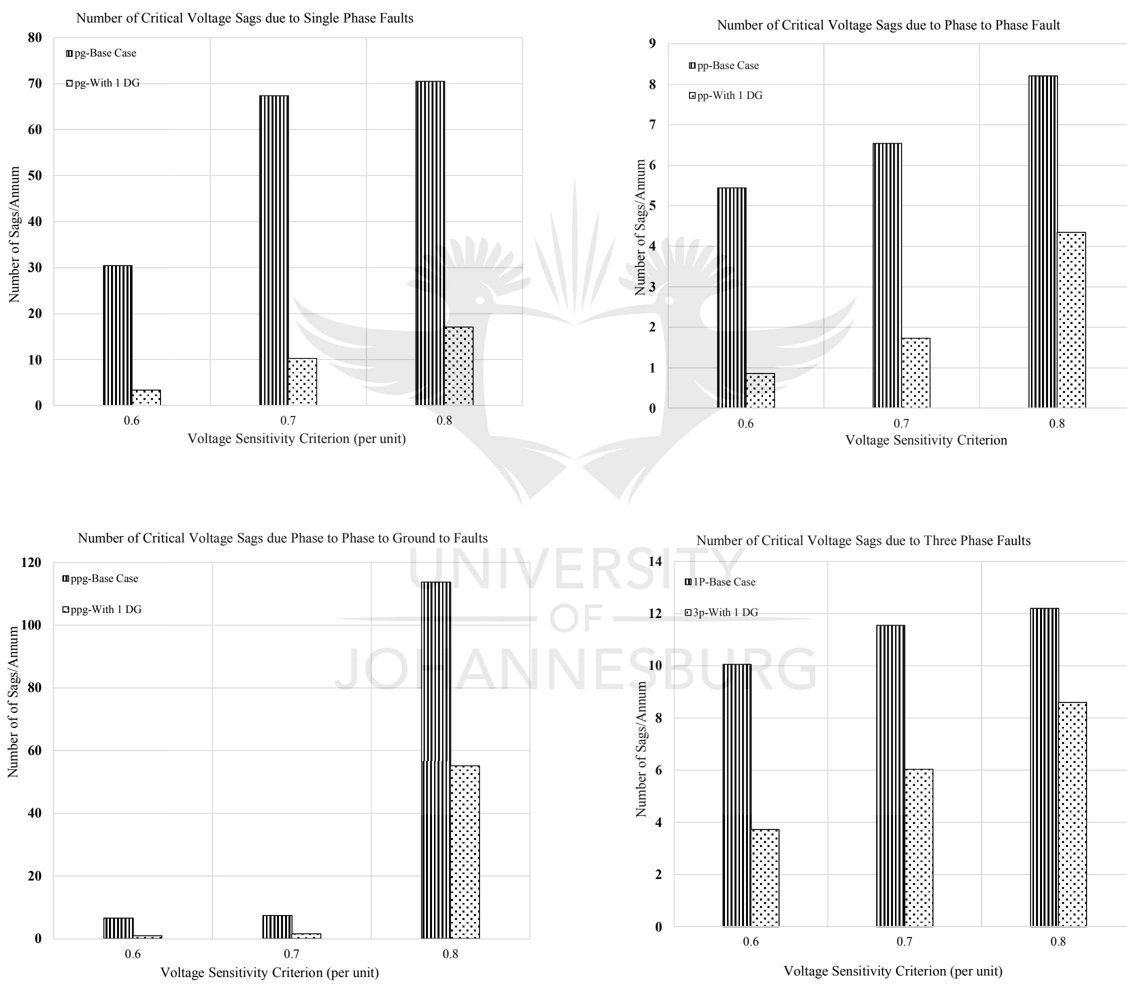

Fig. 15: Critical voltage sags for different criteria and fault types for Base Case and case with DG.

The aforementioned illustration means that if a motor trips at 0.6 per unit kV, it will experience less voltage sags as compared to when it trips at 0.8 per unit kV. It also means that single-phase faults are dominant such that they can cause such voltage sags.

5.5. Estimation of the Cost of Voltage Sags

Most customers currently employ sensitive modern equipment loads, and voltage sag can result in substantial cost due to interruption of the process. These types of loads include but are not limited to robotics, programmable logic controllers, and speed drive control. Because of that, it will be very critical to evaluate the impact of voltage sag mitigation methods such as DG on the economic impact on the performance of such equipment. This equipment is very critical to overall processes of many customers around industries and can lead to a very expensive downtime when there is an interruption. Depending on what type of customer, different customers will suffer different costs in their operations due to voltage sags. The costs assumed in the study are illustrated in *Table 4.*

The cost of critical voltage sag can be categorized as follows:

- production-related losses, which are loss of production or material, loss of production capacity, and disposal charges;
- labor-related losses, such as employees, overtime, cleanup, and repairs; and
- ancillary cost, such as damaged equipment, loss of opportunity cost and penalties due to shipping delays.

Table 4: Interruption cost for different customer types [14].

Type of Load	Sag costs per event (£) of assuming 1 day duration of interruption
Residential	-
Commercial	1 000
Industrial	163 000
Large User	581 000

To explain the interruption cost in *Table 4*, for example, during the interruption, residential customers use different types of equipment loads which are not sensitive to interruption, such as iron, water cattle, and heaters. It is for this reason that during interruption, such equipment will go unnoticed. The same cannot be said of commercial customers such as banks that use mostly computers and servers, as during interruptions, such equipment would have a severe impact.

For Industrial and Large User, the impact becomes even worse due to the sensitivity of their employed equipment such as speed drives and programmable logic controllers. Examples of such industries include but are not limited to car manufacturers, mining, and agriculture. Such customers lose an enormous amount of money for the same interruption experienced by a residential customer, depending on the type of sensitive equipment employed; nevertheless, with residential customers, the interruption went unnoticed.

With the foregoing said, the utility will also experience a challenge when planning to connect such customers, as both parties would want to know the impact of voltage sags on their equipment. Again, as previously mentioned, it will be a very expensive exercise to put measuring equipment on each and every supply point.

The most efficient way to plan such is to use stochastic estimation, which saves money and time. Not only does the sensitivity of loads affect the formulation of the stochastic formula but also the severity of voltage sag has an impact. The equipment used by the customer will be affected differently by occurrence of voltage sags as opposed to interruptions, with all equipment taken out of operation by an interruption and lesser equipment affected if a sag that does not culminate in an interruption occurs. This means that the cost of voltage sag will vary with the severity of voltage sag; these are defined as matrix of weighted factors. These factors are developed using the cost of interruption.

Table 5: Severity of voltage sags depends on weighting factor [18].

Voltage Sag Magnitude Range	**Weighting Factor for Costs in Economic Evaluation**
Interruption	1
Voltage sag with magnitude in the range 60-74%	0.85
Voltage sag with magnitude in the range 75-84%	0.4
Voltage sag with magnitude in the range 85-100%	0.15

Three customer mixes were considered for this study. The load group mixed was Type I, Type II and Type III as illustrated in *Table 6.* The assumption of the load groups is made because the information about the type and nature of voltage sensitivity of the customer equipment is often not available. To improve the resolution of the accuracy of the economic assessment, the general working trends of different types of customer mixes were also considered. The total number of trips multiplied by the correction factor in order to obtain an actual number of trips attributed to each customer category annually is illustrated in *Table 6.* Depending on the type of load, the operation cycles of such loads differ; hence, the correction factor is not the same as illustrated in *Table 6*.

To assess the economic impact of voltage sags, the following information is needed:

- the number and characteristics of voltage sag expected at a specified location over a period of interest;
- the information about the sensitivity of various types of equipment connected; and
- the number of such equipment participating in an industry or commercial process along with their interconnection.

The above relates to information about the average cost claimed by different types of customers at a particular point due to a single trip of process due to voltage sag. Thus far, from above estimation, the cost of voltage event can vary significantly not only among different industry types and individual facilities but also with market conditions. Correction factors are shown in *Table 7*. For example, large users operate 365 days; the factor depends on the operational cycle and hence it is 1. While industrial and commercial customers operate at a different operational cycle, which also differs between them, this study considers and appreciates the important parameters, such as weighting factor, working trend of the customer in terms of correction factor and type of sensitivity to loads, which are basic factors to stochastically estimate the cost of interruption or voltage sags.

Table 6: Different customer load mix used [18].

Load Mix Case No.	Type of Load	Load (%)	Cost/Sag (£)
I	Residential	-	-
	Commercial	-	-
	Industrial	30%	163 k
	Large User	70%	581 k
II	Residential	-	-
	Commercial	9.5%	1 k
	Industrial	75%	163 k
	Large User Large User (Commercial)	9.5% 0.5%	1 k 581 k
III	Residential	50%	0
	Commercial Commercial (Large)	28.5% 1.5%	1 k 581 k
	Industrial	20%	163 k
	Large User	-	-

This study will evaluate the Base Case and compare it with the case of DG in order to analyze the impact of DG economically on voltage sag mitigation.

Table 7: Correction factors for customers used in the study .

Type of Load	Operating Cycle	Correction Factor
Residential	-	-
Commercial	Two days off every week, 8 hours a day operation	0.238
Industrial	One day off per week, 10 hours a day operation	0.357
Large User	Continuous process (365-day operation)	1

The approach for calculating the estimated cost of voltage sags is illustrated in *Table 8*.

Table 8: Calculation of estimated costs of critical voltage sag (assuming 0.8 per unit kV criterion) for single-phase faults.

Type of Fault	Voltage Level	Name of a line	Fraction of Voltage Sags, $\rho_{sag(i)}$	Length of Line (km), l_i	Expected Number of Faults on Line *i* per Annum	Expected Number of Single-phase faults on Line *i* per Annum	Expected Number of Sags per Annum Due to Single-phase faults on Line *i*	Estimated Cost of Critical Voltage Sags due to Single-phase faults
Single Phase-to-Ground	150kV	Line [7-8]	1.000	500	50.00	40.00	40.00	£ 11,518.21
	150kV	Line [7-9]	1.000	100	10.00	8.00	8.00	
	150kV	Line [8-9]	1.000	200	20.00	16.00	16.00	
	20kV	Line [1-2-3-4]	0.333	30	30.00	19.50	6.50	
	20kV	Line [2-5]	0.000	5	5.00	3.25	0.00	
	20kV	Line [3-6]	0.000	5	5.00	3.25	0.00	

To explain *Table 8,* the following can be noted:

- The first column is the type of fault of interest.
- The second column is the voltage.
- The third column is the line.
- The fourth column is the fraction of samples crossing the critical criterion.
- The fifth column is the length of the line.
- The sixth column is the length of the line multiplied by historical data of the probability of occurrence of that particular fault per annum.
- The seventh column is the expected number of a particular fault type in the previous point multiplied by the probability of occurrence of such fault.
- The last column is an addition of the seventh column.

Here, the assumed criterion for occurrence of voltage sag is 0.8 per unit kV. The number of critical voltage sags in bus 1 due to single phase-to-ground faults in this illustration in the system can be calculating by using (10). Once the number of critical voltage sags is determined, the estimated cost of voltage sags due to single phase-to-ground faults can be established by using the expression (11).

The above calculation was then repeated for phase-to-phase, phase-to-phase-to-ground faults, and for three-phase faults. Finally, the total estimated cost of voltage sags is obtained by adding the estimated costs for each of the four fault types.

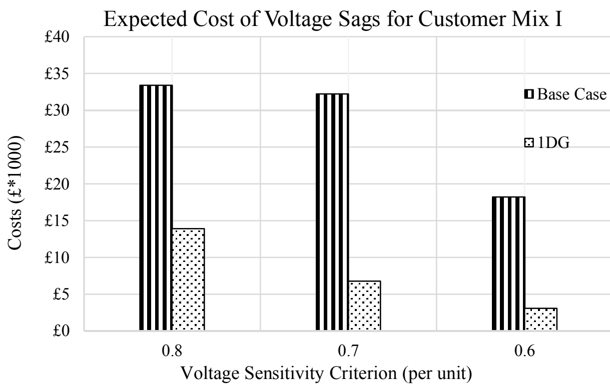

Fig. 16: Estimated cost of voltage sags for Customer Mix(I) for the case with and without DG.

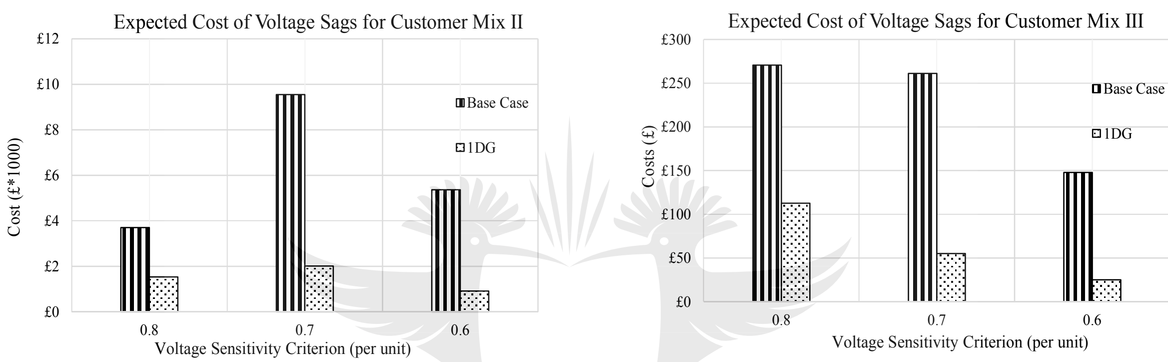

Fig. 17: Estimated cost of voltage sags for Customer Mix(II) and Customer Mix(III) for the case with and without DG.

All voltage criteria of 0.6 per unit kV and 0.7 per unit kV were considered for Customer Mix I, Customer Mix II, and Customer Mix III. The graphs that consolidate all calculations of cost of voltage sags to all customer mixes are illustrated in *Fig. 16* and *Fig. 17* respectively. From the graphs, it is evident that as the voltage sensitivity criteria are tightened (i.e. increased), the expected cost of critical voltage sags generally increases. The exception to this is the 0.8 per unit kV case for Customer Mix II, where costs are lower than for the other two criteria.

This apparent deviation from expectation can be resolved by looking closely at equation 8. Equation 8 shows that the net expected cost of voltage sags is influenced by an interaction between the number of voltage sags, which tends to increase the costs, and the severity of voltage sags, represented by weighting factors that decrease as the severity of sags decreases.

A comparison of the expected costs for the DG Case and Base Case for all the customer mixes evaluated show that the costs are consistently lower for the DG Case compared to the Base Case for all voltage sensitivity criteria, due to the fact that DG mitigated some voltage sags.

The final chapter will provide conclusions of the study and recommendations for future research.

Chapter 6: Conclusions and Proposal for Future Work

6.1. Conclusions

This study has investigated the impact of DG on voltage sag performance. Stochastic prediction of voltage sag performance, based on fault positioning method, was utilized, and the number of critical voltage sags was calculated and analyzed in the study.

The study shows that in the presence of DG, there is a general decrease in the severity of voltage sags; the probability of having a voltage sag is reduced when comparing the Base Case with the case with DG. The study, therefore, demonstrated that DG can reduce the expected number of critical voltage sags and the number of plant trips and, thus, can contribute to reducing financial losses associated with voltage sags. Stochastic prediction was also utilized to evaluate the impact of DG; it has been used to predict voltage sag performance, from which an expected number of critical voltage sags per annum and ultimately the expected cost per annum has been derived.

It has been demonstrated that with the incorporation of DG, in relation to the case without DG, the magnitudes of voltages that remain in the system following faults are improved and become higher, with the expected number of critical voltage sags being reduced. Most significantly, the expected cost of voltage sags is reduced. It has been shown that in addition to documented benefits of incorporating DG resources in power systems, DG can improve voltage sag performance, reduce the likelihood of interruptions of production, and reduce associated expected financial losses.

6.2. Proposal for Future Work

6.2.1 Usage of Other Types of Load Models

In this study, constant power load model was considered. It is proposed that in future other load models, e.g. constant current load model, constant impedance load model and voltage dependence load model, be assessed.

6.2.2 Usage of Other Types of Distributed Generation

The investigation considered distributed generation. It is proposed that a study considering other types of distributed generation, e.g. wind and photovoltaic plants, be considered in future.

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